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Figure 1. Trunk storm sewer west of the collapse, showing structural clay tile construction. The sewer is 5'-6" in diameter and there are 18 tiles around the circumference

Collapse of a Trunk Storm Sewer in Boston

A developer assembled a piece of land on a main street in an urban section of Boston and planned a one-story commercial building with a basement. The developer hired an architect, structural engineer, and site engineer to develop the design and the necessary drawings. The area of the land is approximately 14,500 square feet; however, a sewer easement for a trunk storm sewer crosses the rear portion of the land.

In order to maximize the building footprint (5,500 square feet) and provide the necessary off-street parking, the developer obtained a license from the City to construct a small portion of the building over the storm sewer. Figure 2 shows a plan of the foundation design in the vicinity of the sewer. Figure 5 *(on page 3)* shows a schematic section through the building foundation and the sewer, as designed. The section is taken as indicated on Figure 2.

The City's records of the trunk storm sewer are meager; they only indicate that it was constructed either in 1902 or in 1914, that it had an inside diameter of 5'-6", and that it had an inside surface of concrete. Based on this information, the site engineer and the City both assumed that the sewer was constructed from concrete; however, neither of them knew whether the concrete was reinforced (with steel) or

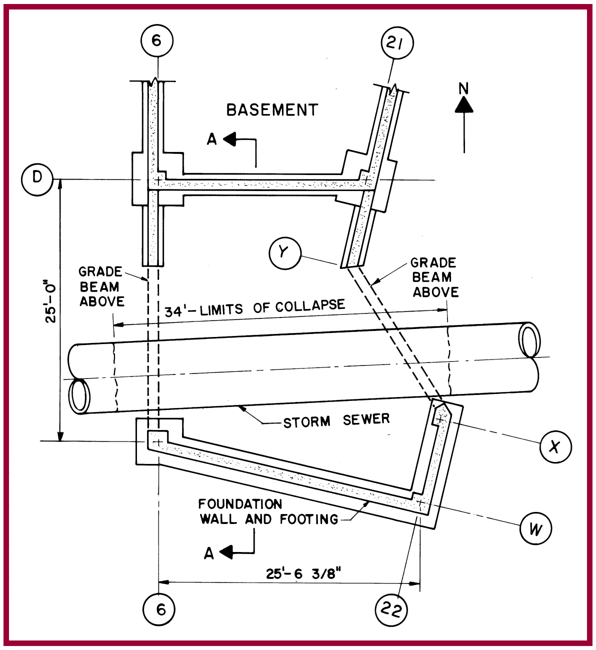

Figure 2. Foundation plan in the vicinity of the storm sewer, as designed.

not. The site engineer indicated that the sewer was of concrete construction on his site plan. The structural engineer did not show the sewer on his drawings, or otherwise address the sewer; he only indicated the limits of the sewer easement on his foundation plan.

As part of the license agreement for building over the sewer, the City required that the developer have a video made of the condition of the sewer prior to construction. The required video was made by a robot specially designed for the purpose, and the making of the video was witnessed by the developer. At that time, the developer discovered that the sewer was of clay tile construction, not concrete; however, he did not inform the City or anyone else of the changed condition. Figure 1 is a photo of the inside of the sewer showing the clay tile construction.

The developer was also the general contractor for the project. He first constructed the foundation for the portion of the building with a basement, which runs from Line D northward (see Figure 2), and then proceeded to build the portion of the foundation south of Line D.

The Collapse

The excavation subcontractor used a large hydraulic excavator on tracks which stays on the top of the bank, excavates down into the excavation, and moves backwards as it excavates (called a backhoe). For the excavation work south of Line D, the excavation subcontractor first excavated trenches for the short extension wall and the grade beam on Line 6 (see Figure 2), for the short extension wall on Line 21, and for the grade beam from grid point Y-21 to grid point X-22. The excavation subcontractor then excavated a trench for the foundation wall on Line W, which is south of the sewer, moving from grid points W-6 to W-22, and finally excavated for the short wall on Line 22. The depth of the trench for the wall on Line W was just below mid-height of the sewer (see Figure 5).

Figure 3. Collapsed storm sewer at the west end of the collapse, looking northwest.

Figure 4. West end of collapsed storm sewer, showing details of the clay tile construction.

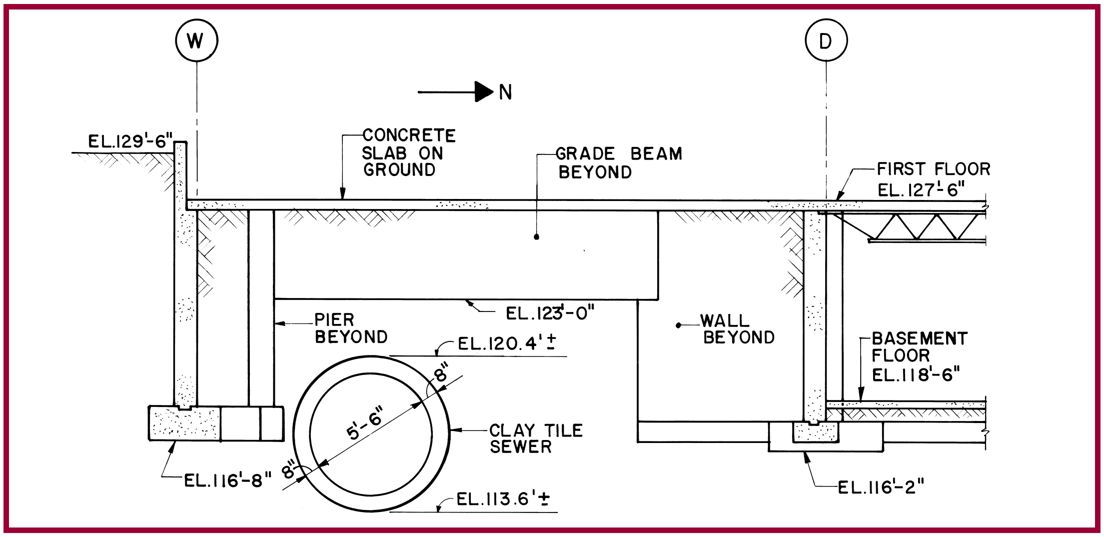

Figure 5. Section A-A, through the foundation and storm sewer. See Figure 2 for location.

The sewer collapsed just after the excavation subcontractor completed his work and parked his machine beyond the southeast corner of the excavation. Figure 2 shows the extent of the collapse, Figure 3 shows a portion of the collapsed sewer, and Figure 4 shows details of its clay tile masonry construction. The depth of the soil over the top of the sewer, just before the collapse, was approximately 3 feet where the grade beam trenches crossed over the sewer, and 8 feet between the grade beam trenches.

The clay tile masonry sewer was constructed in-place, with the use of formwork and shoring. The sewer has a circular ring shape, which can be envisioned as two arches, one arch on top of a second inverted arch. See Figures 1 and 6. The lateral soil pressure on each side of the sewer provides the lateral thrust on each side that is necessary for the stability of the “two arches.”[1] When the soil was excavated on one side (the south side) of the sewer for a length of approximately 34 feet, a substantial portion of the lateral soil pressure against the side of the sewer ring was removed. See Figure 7. This loss of lateral pressure resulted in a substantial loss of lateral thrust and an asymmetrical loading condition, which caused the collapse of the sewer.

Design Issues

In his design, the structural engineer apparently did not consider the possible vulnerability of the storm sewer. Although he had the right to rely on the site drawing that indicated that the sewer was of concrete construction, he could not have known the strength of the concrete, the thickness of the wall of the sewer ring, or if the concrete was reinforced. Although concrete has a higher tensile strength than clay tile masonry, the behavior of a sewer ring of unreinforced concrete would be similar to that of a sewer ring of masonry. Even if the concrete was reinforced, the structural engineer had no way of knowing the bending strength of the sewer wall.[2] The structural engineer should have used a foundation system south of Line D which would have avoided a large, deep and continuous excavation next to the sewer. A simple method of doing so would have been the use of grade beams supported by caissons,[3] as shown in Figure 8 *(on page 5)*. The caissons would have extended down to the same elevation as the bottom of the sewer, and the bottom of the excavation for the grade beams could have been 3 feet or more above the top of the sewer. Excavating the caissons next to the sewer would not have endangered the sewer, since the shaft of the caisson would not have been much larger than three feet in diameter, and adjoining lengths of the sewer would have provided adequate support for the small length of sewer which may have been temporarily weakened due to the construction of the caisson shaft.[4]

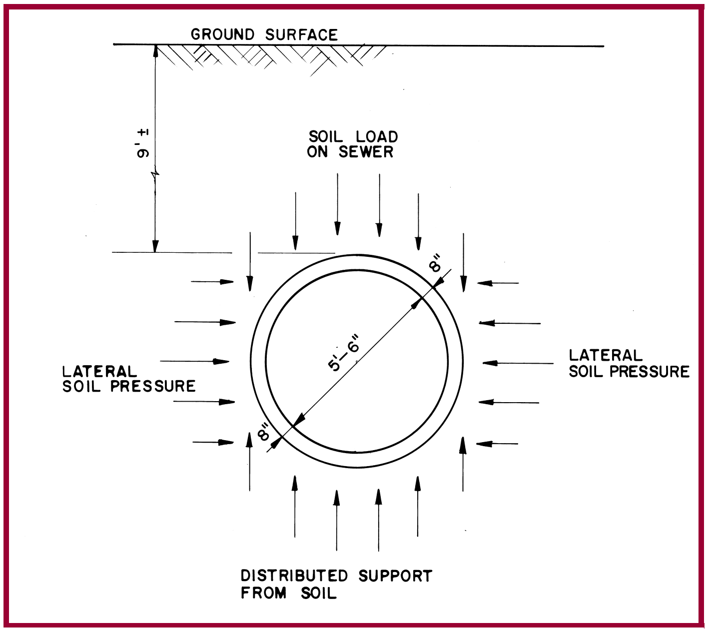

Figure 6. Section through the storm sewer, showing conditions prior to excavation and soil pressures on the sewer.

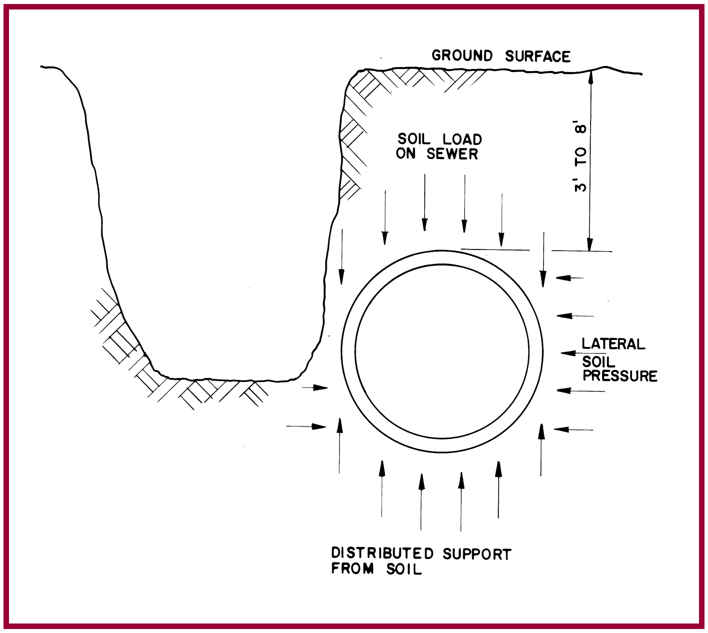

Figure 7. Section through the storm sewer showing conditions just prior to the collapse. Lateral soil pressures on the sewer were substantially reduced by the excavation on one side of the sewer.

End Notes

1. See On-Line Issue No. 15 of *Forensic Engineering in Construction* which explains beam and arch action to non-engineers.

2. A reinforced concrete ring, such as a reinforced concrete sewer pipe, behaves differently than an arch. When loaded vertically, large bending moments are created at the top, bottom, and at mid-height of the two sides. If properly designed to resist the bending, the ring is self-contained and does not need exterior lateral thrusts for stability.

(Continued of Page 5)

End Notes (Continued)

3. A caisson is a drilled or hand excavated round pier. A shaft is excavated with a round steel casing. The casing is installed, telescope fashion, as excavation proceeds downward. When the shaft reaches the proper depth, the shaft is filled with concrete, and the casing is pulled out as the concrete fills the shaft.

4. The structural engineer’s design was also faulty in another regard: as shown in Figure 5, the bottom of the footing of the wall on Line W is at the approximate mid-height of the sewer; it should have been at the bottom of the sewer. At mid-height, where the footing is close to the sewer, the vertical pressure of the footing on the soil would have caused the soil to exert high lateral pressures on the sewer ring, which would have damaged the sewer.

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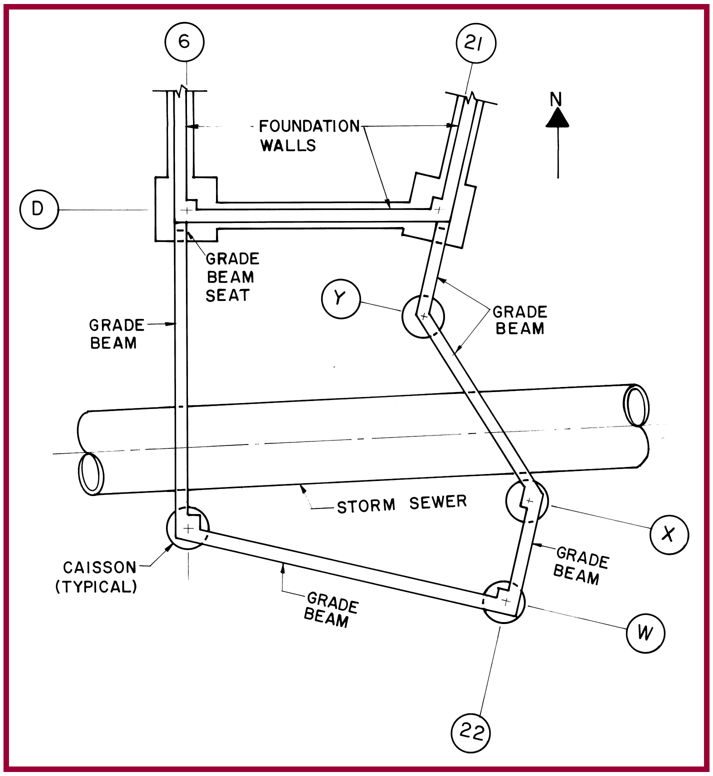

Figure 8. Plan showing foundation design utilizing grade beams and caissons south of Line D. Bottom of grade beams would be 3 feet or more above the top of the sewer.

Principal Rubin M. Zallen, P.E. investigated this failure. He has developed a limit-state analysis method for analyzing unreinforced masonry arches, pipelines, beams, and piers, which accounts for the cracking of these members.